Summary Report for the Snowmass Agora #2 On Future Colliders: Circular e^+e^- Colliders

Moderators: Sarah Eno and John Seeman

Introduction:

As part of the Snowmass 2021 Community Planning Process, the Accelerator and Energy Frontiers announced a series of events, intended for all Snowmass participants, to discuss physics and technical aspects of different collider concepts.

The second of these virtual events, on **Circular e^+e^- Colliders**, was held on January 19, 2022. The 2.5 hour event consisted of one particle physics talk followed by four accelerator talks covering five potential future circular e^+e^- collider accelerators. For the majority of these talks concentrated on accelerators with center-of-mass energies for Z, W, H, and ttbar. The last hour was concentrated on a community Q&A session covering physics and accelerator topics answered by the respective speakers.

Physics at Z, WW, H, and tt – Alain Blondel:

The discovery of the Higgs boson opens a new frontier for exploration. It is the only known fundamental scalar, and the only particle with a non-zero vacuum expectation value. In the standard model (SM), it is predicted to couple to fermions by Yukawa couplings that are equal to their masses. This prediction must be tested, but the origin of the seemingly arbitrary mass values is unknown. A circular electron-positron collider can make precision measurements of the Higgs mass, width, and couplings. The Higgs coupling to the Z is especially important, as it can serve as the normalization of all other measurements at previous or later colliders. Precision studies can give access, either by mixing with possible additional spin 0 particles, or via loop corrections, to new physics that couple to this unusual particle. Thus the physics of a circular electron-positron collider is the physics of a Higgs factory. However it is also so much more.

Circular electron-positron colliders are versatile facilities which allow accumulation of very large samples of all the heavy known SM particles (e.g. for the current FCC-ee run plan 5×10^{12} Z's, 10^8 W' pairs, 10^6 Higgs, 10^6 top pairs, 10^{11} tau pairs, and 10^{12} bottom pairs), allowing precision measurements of their properties and of the parameters of the SM, indirect probes of high energy scales, and searches for new particles, especially towards weaker couplings. An attractive feature is the possibility of four interaction regions with different detectors, allowing multiplication of the acquired sample size and the best energy efficiency of all proposed Higgs factory options. A new large diameter ring has a compelling upgrade path: an energy-frontier hadron collider, with a complementary and synergistic physics program, a direct reach for new particle discovery similar to the indirect sensitivity provided by the electron-positron studies, and allowing precision measurements that are statistics limited at electron-positron machines (such as the muon and top Yukawa couplings, the Higgs self-coupling, and the higher-order couplings to $\gamma\gamma$ and $Z\gamma$). A heavy ion collision program is foreseen as well as an electron-proton option allowing interesting studies of the strong force.

Running above the threshold for ZH production will allow very clean production of the Higgs boson. The ZH events can be determined independent of decay mode and with complete model independence by reconstructing the "recoil" mass using the measured Z 4-momenta and the center-of-mass constraints . The uncertainty on the Higgs boson mass can be reduced to a few MeV and that of its width to 40 keV. Higgs couplings to W, b, c and tau will be measured to the percent level, that to the W down to the per mil level. These measurements probe scales up to 7 TeV for new physics interacting with the Higgs sector with SM couplings. If a Neutral Lepton is discovered in Z decays, the existence of a Yukawa coupling to neutrinos could be established. At FCC-ee, the Higgs coupling to electrons can be probed with a dedicated run at the Higgs mass down to 1.6 times the SM value or possibly better. The Higgs self-coupling can be measured to 5% with the subsequent proton collider.

The intense beams possible for circular machines running at the Z center-of-mass energy make possible a plethora of indirect probes of new physics and measurements of the SM parameters. Uncertainties on electroweak observables will be considerably reduced, e.g. two orders of magnitude for the weak mixing angle $\sin^2\theta_W$ or the Z width, and potentially more for some heavy flavor or tau observables. The uncertainty on the top mass can be reduced by an order of magnitude. These precision measurements provide sensitivity to scales up approximately 50 TeV for SM-coupled new heavy particles and for specific models sometimes more (e.g. heavy neutrinos can be probed to 500-1000 TeV via their mixing with the light ones.). Uncertainties on tau lepton observables will be decreased by 1-3 orders of magnitude. Samples of b quarks 20 times larger than those predicted to be accumulated at Belle-II will allow further elucidation of the current discrepancies seen in lepton universality in b decays and further understanding of the dominant sources of CP violation

The uncertainty on α_s can be decreased from its current uncertainty of 0.6% to better than 0.1%.

The combined run plan will also greatly extend the reach for direct searches for new feebly-coupled particles, such as axion-like particles and heavy neutral leptons

The presentation led to a lively question and answer period, with much interest from the participants. A wiki page with answers to questions provided before the agora via a solicitation can be found at: https://docs.google.com/document/d/1jgPcDDpxzwMbdrvqA4KnNC58IDlQmLz_dxRDPu3VUuM/edit?usp=sharing

FCCee e$^+$e$^-$ Collider– Frank Zimmermann and Michael Benedikt

Overview: The proposed circular FCCee is a well-studied e$^+$e$^-$ collider to be located surrounding CERN and Geneva. The double-ring collider would operate at four CM energies albeit needing very different beam parameters ranging from the *Z* (91 GeV cme) to *ttbar* (365 GeV cme). The present optimized main tunnel length is 91.2 km. A schematic is shown below. Ampere level bunched beams maintained by SC RF cavities would be circulated in the two rings, one per beam, and made to collide in up to four interaction regions. The projected luminosity per IP ranges from 1.8x10^{36}/cm^2/s at the *Z* to 1.25x10^{34}/cm^2/s at the *ttbar* within the limit of 50 MW of synchrotron radiation power loss per beam. A full energy injector located in the same tunnel would top-up the beam currents in the two colliding rings. The injector would reuse significant parts of the present CERN infrastructure. A CDR has been written in 2018 (with 2 IPs) and recently updated to a 4-IP lattice. Significant design efforts and R&D have been completed including lattice, magnets, IR, site, and staging. The crucial future technical R&D will concentrate on the 7.7 GeV SC RF cavity systems including HOM(high order modes) damping with ampere level bunched beams and, also, highly efficient RF klystrons. The magnet systems have very low fields to minimize the synchrotron radiation power. Considerable attention is given to the interaction region for clean experimental conditions, and to the center-of-mass energy calibration, especially at Z and W energies with resonant depolarization.

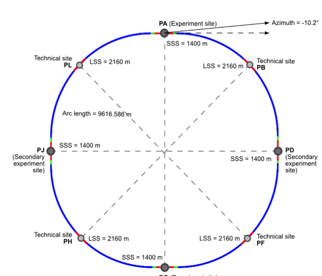
Main advantages: Circular e$^+$e$^-$ colliders overall have a successful 50 year history including LEP at CERN. Multi-ampere beams have been demonstrated at PEP-II and KEKB. The SuperKEKB e$^+$e$^-$ collider in Tsukuba, now in operation, will demonstrate in the next few years nearly all the required accelerator physics techniques for FCCee, as will the future electron ring for the EIC at Brookhaven.

Main challenges: The peak luminosity within given synchrotron radiation power limit drops at higher beam energies approximately as $1/E^3$. Crab waist collision scheme with a large crossing angle, high bunch charges and mm-level vertical beam beta functions needs solid verification. SC RF cavities with multi-ampere beams with strong HOM damping require reliable demonstrations. Studies are ongoing for cost and power reduction.

Pre-project cost and schedule: Technically, the project is nearly ready to proceed. R&D and prototyping is ongoing. However, the project needs to wait for the LHC-HL operational program to be completed leading to a start date for FCCee of around 2042.

Project construction time and cost: The project cost for *Z* (91 GeV cme) to *ZH* (240 GeV cme) operation is projected by the proponents to be about 10.5 BCHF (in 2021) using European accounting. Add 1.1 BCHF for the RF needed to go to *ttbar*.

The feasibility study of FCC has been approved by council and launched, technical study addressing all aspects but the financial study concentrated on the tunnel and the first collider (FCC-ee) .



FCCee Overview with IRs for up to four detectors (Circumference ~91.2 km).

CEPC e⁺e⁻ Collider -- Jie Gao

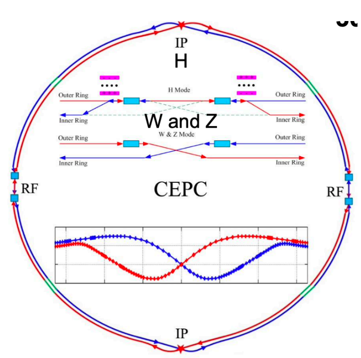
Overview: The proposed circular CEPC is a well-advanced e^+e^- collider to be located at one of several potential sites in China. The collider would operate at four CM energies although needing very different beam parameters ranging from the *Z* to *ttbar*. The present optimized main tunnel length is 100.0 km. A schematic is shown below. Ampere level bunched beams maintained by SC RF cavities would be circulated in the two rings, one per beam, and made to collide in up to two interaction regions. The projected luminosity ranges from $1.15\text{x}10^{36}/\text{cm}^2/\text{s}$ at the Z to $0.5\text{x}10^{34}/\text{cm}^2/\text{s}$ at the ttbar. A full energy injector located in the same tunnel would top-up the beam currents in the two colliding rings. The injector would be a new accelerator. A CDR has been completed and a TDR is due within a year. Significant design efforts and R&D activities are underway including hardware prototypes of SC RF cryomodules, RF cavities, efficient klystrons (now up to 65%), vacuum chambers, and magnets. The magnet systems have very low fields to minimize the synchrotron radiation power.

Main advantages: Circular e^+e^- colliders overall have a successful 50 year history including BEPC-II at IHEP in Beijing. Multi-ampere e+ and e- beams have been demonstrated in PEP-II and KEKB. The SuperKEKB e^+e^- collider in Tsukuba, now in operation, will demonstrate in the next few years nearly all the required accelerator physics techniques for CEPC, as will the future e- ring of the EIC at Brookhaven.

Main challenges: The peak luminosity drops at higher beam energies. Crab waist collision scheme with high bunch charges and mm-level vertical beam beta functions needs solid verification. SC RF cavities with multi-ampere beams with strong HOM(high order modes) damping need reliable demonstrations. Studies are ongoing for cost and power reduction.

Pre-project cost and schedule: Technically, the project is nearly ready to proceed. Pre-construction R&D and prototyping is ongoing. Future crucial technical R&D will concentrate on the 10 GeV SC RF cavity platforms including HOM damping with ampere level bunched beams and highly efficient RF klystrons. The project is trying to take advantage of situations uniquely available to Chinese construction.

Project construction time and cost: An international collaboration is under development. Construction may start around 2026 followed by data taking perhaps starting around 2034. The project cost is projected by the proponents to be about 5 BUS$ (in 2021) for the Higgs based collider using Chinese accounting.



CEPC collider ring (100km)

FNAL e^+e^- Site Filler (ie LEP3 Collider at FNAL) – Eliana Gianfelice-Wendt

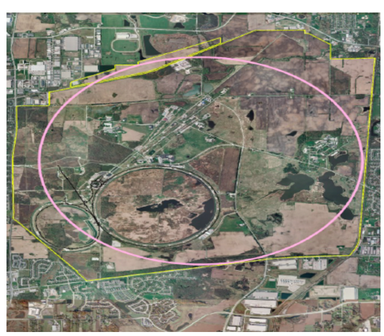
Overview: The "Site Filler" is a proposed circular e^+e^- collider in a very early development stage to be located on the FNAL site. A schematic is shown below. The single ring collider would operate at 46-120 GeV per beam with only a few bunches (2 to 4) colliding head-on. A luminosity at the Z (91 GeV cme) would be about $6.3\text{x}10^{34}/\text{cm}^2/\text{s}$ and at the Higgs about $1.0\text{x}10^{34}/\text{cm}^2/\text{s}$ with the total synchrotron radiation power limited at P_{SR}=2×50 MW. The main tunnel is C=16 km in length corresponding to the maximum possible circumference on the existing FNAL site with one IR. A top-up injector may be required and would be mostly new, however, with some present FNAL infrastructure gainfully repurposed. In the near term, the basic beam parameters need to be optimized and then the basic technical accelerator components will be designed. The future needed R&D concentrates on the basic accelerator design followed by the specific component designs. Later on, R&D will concentrate on the design of the ~12 GeV SC RF cavity system including HOM damping with ampere level bunched beams and on highly efficient RF klystrons.

Main advantages : Circular e^+e^- colliders overall have a successful 50 year history. Multi-ampere beams have been demonstrated. The SuperKEKB e^+e^- collider in Tsukuba, now in operation, will demonstrate in the next few years nearly all the required accelerator physics techniques, as will the future EIC at Brookhaven. US circular collider experts are available. The construction time for this collider is relatively short due to the available site and small circumference.

Main challenges: The peak luminosity scales approximately as $P_{SR}\, C\,/E^3$ and not only drops at higher beam energies, but also is lower for smaller circumference of the "Site Filler" relative to FCCee (91 km) and CEPC (100 km). Strong synchrotron radiation reduces the available beam currents. The equilibrium beam emittances for smaller rings are large reducing the number of colliding bunches.

Pre-project cost and schedule: The pre-construction costs and schedules are smaller due to similar R&D on lattices and hardware done elsewhere.

Project construction time and cost: Costs are under development. Construction time should take about 7 years.



FNAL e+e- Site Filler Overview (Circumference ~16 km)

CERC e^+e^- Collider – Vladimir Litvinenko

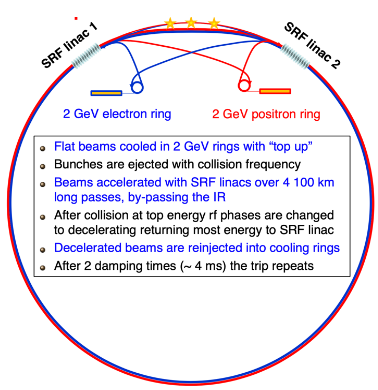
Overview: CERC (**C**ircular **ER**L **C**ollider) is a “particle and energy” recovery e^+e^- collider aiming at an extendable energy reach starting at the *Z* (91 GeV cme) and can go to 600 GeV cme scale. This collider is early in the design process. A schematic is shown below. The luminosity would be $93 \times 10^{34}/cm^2/s$ at the *ZH* (240 GeV cme) to $4.4 \times 10^{34}/cm^2/s$ at 600 GeV cme with (only) 30 MW of synchrotron radiation The concept entails beams from damping rings are injected into a sequence of four parallel magnet rings per beam in a 100 km tunnel. The beams make four passes in the rings bypassing the IR and being accelerated to the energy of collisions by about 10 to 75 GeV per turn. The beams are made to collide at several potential interaction points with small (flat) y-to-x size aspect ratios. Then the beams are redirected back to the four rings to be decelerated over four turns recovering the energy and reinjected into the damping rings to recover the particles. The low energy damping rings reduce the enlarged beam emittances from the collisions. A low-power injector replenishes any small particle losses. Both beams can be longitudinally polarized at the IP. The polarization beams are thus “recycled”.

Main advantages: ~~T~~he beam energy recovery allows many more particles and bunches to be accelerated with a fixed site power. This allows the collision rate to be scaled up until the synchrotron radiation and various small power losses sum to the site power limits. Particles are recovered so the beam source requirements are greatly reduced. The beam energy is largely recovered so the accelerator power required for increases in beam energy is smaller than for traditional circular e+e- colliders.

Main challenges: Four 100 km rings are required with tight tolerances. The SC RF systems are quite long and expensive. Deposited HOMs in the SC RF cavities may cause beam displacements leading to emittance growths. The enlarged beam emittances (transverse and longitudinal) exiting from the non-linear strong beam-beam interaction may cause extra particle recovery losses. The IR design becomes more complicated to accommodate for beam and energy recovery. Accelerator error tolerance studies are needed.

Pre-project time and cost: R&D of 5 years is needed. All nominal technologies have been largely demonstrated with existing accelerators or investigated for other future collider designs. Large SCRF systems need study. Front-to-end accelerator layout, component designs, and beam physics simulations need to be optimized.

Project construction time and cost: Construction start could be 2030. Construction time is approximately 10 years. Costs are under investigation by the proponents.



CERC ERL e+e- Collider (Circumference ~100 km)

ReLiC e^+e^- Collider -- Vladimir Litvinenko

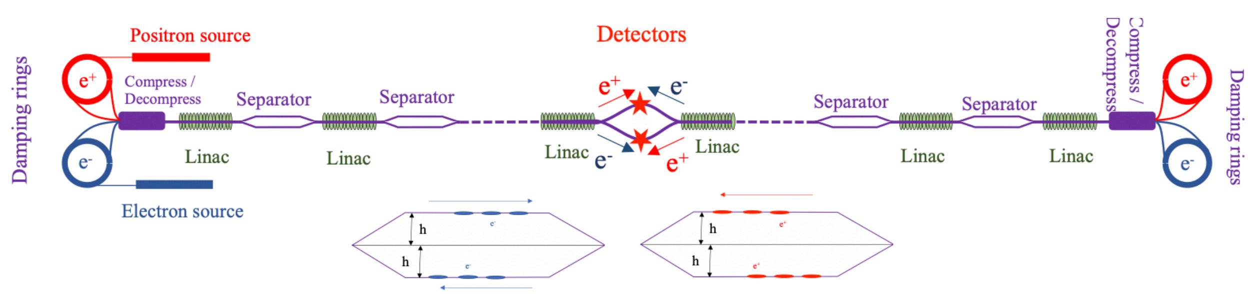
Overview: The ReLiC (**Re**cycling **L**inear **C**ollider) is a "particle and energy" recovery e^+e^- collider aiming at an extendable energy reach starting at the *Z* (91 GeV cme) and can go to the TeV scale. This collider is very early in the design process. A schematic is shown below. The luminosity would be $2.1 \times 10^{34}/cm^2/s$ at the *ZH* (250 GeV) to $0.66 \times 10^{36}/cm^2/s$ at 3 TeV cme. The concept entails four beams (e+e- and e+e-) from a pair of damping rings at each end of two linacs get accelerated with SC RF passing separation chicanes along the way to avoid undesired collisions with decelerated beams. The beams are made to collide only at two interaction point with small (flat) y-to-x size aspect ratios. Then they are redirected towards the opposite linac, decelerated recovering the energy, and reinjected into the damping rings to recover the particles. The damping rings reduce the enlarged beam emittances from the collisions. A low-power injector replenishes any small particle losses. Both beams can be longitudinally polarized at the IP.

Main advantages: The luminosity is higher at higher beam energy. The beam energy recovery allows many more particles and bunches to be accelerated with a fixed site power. This allows the collision rate to be scaled up until the various small power losses sum to the site power limits. The center-of-mass energy scales with linac length. Particles are recovered so the beam source requirements are greatly reduced. The beam energy is largely recovered so the accelerator power required for a large increase in beam energy is small.

Main challenges: Two long SC linacs are required with tight tolerances. The enlarged beam emittances (transverse and longitudinal) exiting from the non-linear strong beam-beam interaction may cause extra particle recovery losses. The chicanes consisting of magnetic and electrostatic separators will become longer at high energies to reduce extra emittance enlargement avoiding a reduced luminosity, as well as adding to the required tunnel length (in addition to the RF length). Deposited HOMs in the SC RF cavities may cause beam displacements in both beams leading to emittance growths. The IR design becomes more complicated to accommodate for beam and energy recovery. Accelerator error tolerance studies are needed.

Pre-project time and cost: R&D covering 5 years is anticipated. All nominal technologies have been largely demonstrated with existing accelerators or investigated for other future collider designs. Front-to-end accelerator layout, component designs, and beam physics simulations need to be optimized.

Project construction time and cost: Construction start could be 2035. Construction duration and costs are under investigation by the proponents.



ReLiC e+e- collider with expandable length and energy and particle recovery (length ~20 to ~360 km).